Wet-Milling Characteristics of 10 Lines from Germplasm Enhancement of Maize Project Compared with Five Corn Belt Lines

Oswaldo Taboada-Gaytan,[1] Linda M. Pollak,[2,3] Lawrence A. Johnson,[4] and Steven R. Fox[4]

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ABSTRACT

The use of corn (*Zea mays* L.) hybrids with high grain yield and starch extractability has steadily increased in the processing industry. In light of widespread corn seed industry participation in the Germplasm Enhancement of Maize Project (GEM), which seeks to enhance exotic germplasm, future hybrids may contain more exotic sources in genetic backgrounds. It is necessary to establish and monitor physical, compositional, and milling characteristics of the new exotic breeding materials to determine the processing value. The present study was conducted to determine the wet-milling characteristics of a set of GEM lines compared with typical Corn Belt lines. Ten GEM lines introgressed with exotic materials from Argentina, Chile, Cuba, Florida, and Uruguay and previously identified as having different starch yields, three commercial inbred lines, and two public inbred lines (B73 and Mo17) were analyzed using both near-infrared transmittance (NIT) and a 100-g wet-milling procedure. There were statistical differences ($P < 0.05$) in the yield of wet-milled fractions (starch, fiber, gluten, and germ). The GEM lines AR16035:S19-227-1-B and CUBA117:S1520-562-1-B had similar or better starch yield and starch recovery than B73 and the other adapted inbred lines, indicating that they may be useful in improving the proportion of extractable starch present in kernels of hybrids. Residual protein levels in the starch and gluten fractions were 0.26–0.32% and 38–45%, respectively. The starch yield of GEM lines from wet milling correlated positively with starch content from NIT and was negatively correlated with protein content of the corn kernels. Oil content in the germ varied from 50 to 60%. Our results indicate that incorporating GEM lines in a breeding program can maintain or even improve wet-milling characteristics of Corn Belt materials if lines with appropriate traits are used.

Corn or maize (*Zea mays* L.) is the most important crop in the United States and starch is the most abundant component of the corn kernels. Use of corn to produce food and industrial products has increased (Dijkhuizen et al 1998; Singh et al 2001; Butzen and Hobbs 2002). In 2006, 33% of the corn production was processed to produce ethanol, sweeteners (high fructose corn syrup, glucose, and dextrose), starch, and other fermentation products (USDA 2007).

Hybrids with high grain yield and higher starch, protein, or oil contents are available to growers. These hybrids are the result of crossing adapted inbred lines, but rarely has exotic germplasm been crossed with elite inbreds to develop new and useful breeding lines (Singh et al 2001). Breeders need sources of genetic variation to develop new lines and hybrids (Salhuana and Smith 1998). Despite its utility as a source of variation for crop improvement, exotic germplasm has seldom been used in advanced breeding programs. In fact, <1% of the U.S. corn germplasm base had an exotic origin in 1984 (Goodman 1985), only increasing to ≈3% in 1996 (Goodman 1999). Because researchers realized that exotic materials in breeding programs are valuable to obtain useful breeding lines, the GEM project, a coordinated and cooperative effort among public and private sectors, was developed to improve and expand the germplasm base of corn used to develop new hybrids with better agronomic performance and value-added characteristics (Pollak 2003). GEM followed the Latin American Maize Project (LAMP), a coordinated international project to evaluate maize genetic resources (Salhuana et al 1991). In GEM, the highest yielding exotic germplasm accessions from LAMP were crossed to a proprietary inbred line to make a 50% exotic breeding cross and then crossed to another adapted inbred line of the same heterotic group to produce a 25% exotic breeding cross. These breeding crosses were yield tested as test crosses and the best ones were used to develop new inbred lines (Salhuana et al 1998) as described by Pollak (2003).

There are few published studies about physical, compositional, and wet-milling characteristics of inbred lines and hybrids or of exotic germplasm. Zehr et al (1995) evaluated wet-milling characteristics on 15 Corn Belt inbred lines and 20 related hybrids. They observed significant divergence of hybrids from the average value of both parents and attributed the lower values for germ and fiber and the higher values of gluten and filtrate solids to the bigger kernel size of the hybrids. A positive correlation between starch yield and starch content and a negative correlation between grain hardness and starch yield were also reported. Singh et al (2001) studied the compositional, physical, and wet-milling properties of 49 LAMP accessions used in GEM, two commercial hybrids, and the public inbred lines B73 and Mo17. They reported lower starch and higher protein contents for accessions than for either commercial hybrids or Corn Belt lines. Absolute densities were also higher for accessions. Their conclusion was that lower values for absolute densities and test weights as well as greater starch and lower protein contents are desirable characteristics that would improve the wet-milling properties of a corn sample.

Based on wet-milling information provided from the GEM cooperator Cerestar (Hammond, IN, now acquired by Cargill, Minneapolis, MN), 10 GEM lines were selected to study the wet-milling properties of elite inbred lines introgressed with exotic germplasm. Our work is a continuation of Singh et al (2001) to know the effect on wet-milling characteristics of crossing adapted inbred lines to LAMP accessions, then using pedigree selection to make exotic introgressed lines. The objectives of this project were 1) to determine the physical, compositional, and wet-milling characteristics of 10 exotic lines from the GEM project, three commercial inbred lines, and two public inbred lines used as checks, and 2) to determine whether GEM lines had better wet-milling properties than the accessions. Our hypothesis was that there are exotic introgressed corn lines from GEM with similar or better wet-milling characteristics than the commercial and public inbred lines.

[1] Graduate assistant, Dept. Agronomy, Iowa State University, Ames, IA 50011.
[2] Research geneticist, USDA-ARS Corn Insects and Crop Genetics Research Unit, Department of Agronomy, Iowa State University, Ames, IA 50011. Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may also be suitable.
[3] Corresponding author. E-mail: linda.pollak@ars.usda.gov
[4] Research technician and professor/director, Center for Crops Utilization Research and Department of Food Science and Human Nutrition, Iowa State University, Ames, IA 50011.

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MATERIALS AND METHODS

Genetic Materials

The GEM lines originally underwent pedigree selection from exotic accessions by adapted lines breeding crosses, were selected for grain yield as test crosses of S_2 lines crossed to commercial testers, and then were evaluated for wet-milling properties by the private cooperator Cerestar. Ten corn lines from the GEM project Sets A and C (http://www.public.iastate.edu/~usda-gem/Official_Documents/GEM_Documents.htm) were used in this study. The lines were selected on the basis of extracted starch yield from the Cerestar data. Highest and lowest starch-yielding lines for each of five germplasm sources were chosen.The lines had 25% exotic genetic background from Argentina, Chile, Cuba, Florida, and Uruguay and were grouped according to starch yield from wet milling as high-starch exotic lines (HSEL): AR16035:S19-285-1-B (AR285), CH05015:N15-182-1-B (CH182), CUBA117: S1520-562-1-B (CU562), FS8B(T):N1802-35-1-B (FS35), and UR13085: N0215-11-1-B (UR11); low-starch exotic lines (LSEL): AR 16035: S19-227-1-B (AR227), CH05015:N15-143-1-B (CH143), CUBA 117:S1520-153-1-B (CU153), FS8B(T):N1802-32-1-B (FS32), and UR13085:N0215-14-1-B (UR14, released as GEMN-0047). Three commercial inbred lines (Line 1, Line 2, and Line 3) that provide different starch contents to hybrid progeny were also included. Seed of commercial lines was provided by Golden Harvest Seeds (Clinton, IL, now acquired by Syngenta, Wilmington, DE). B73 and Mo17, two formerly widely used public inbred lines, were included as checks. The commercial and public inbred lines were classified into a third group as adapted germplasm.

Sample Preparation

Seed of the lines was produced in Ames, IA, in the summer of 2003 by self-pollination. All the ears from a two-row plot (3.8 m long and 76 cm between rows) were hand-harvested and allowed to dry to ≈10% moisture content by circulating warm air at 38°C (100°F) for 72 hr. Seed from all ears within a line was bulked after shelling and stored at 4°C until used. The 100-g samples were handpicked and any foreign material and cracked or broken kernels were removed. Two laboratory replicates per sample were used to determine the physical, compositional, and wet-milling characteristics of the corn lines in this study.

Physical Characteristics

Three variables were quantified to determine the physical characteristics of the corn lines: test weight, 1000-kernel weight, and absolute density. Test weight is a measure of the weight per unit of volume of a grain at a standardized moisture level. In U.S. grain trading transactions, this is normally expressed in pounds per bushel. Standards and procedures to estimate test weights are provided by the USDA Grain Inspection, Packers and Stockyards Administration (GIPSA). In this case, test weight was determined by following the Federal Grain Inspection Services procedures (FGIS 1988) and expressed as kilograms per hectoliter (kg/hL). The 1000-kernel weight (g) was measured using an electronic counter (electronic counter model 850-2, International Marketing and Design, San Antonio, TX) to count kernels and then weigh them in a precision top-loading balance (OHAUS Explorer Pro model EP4102C, Pine Brook, NJ). Absolute density is a measurement of the volume of a specified weight of kernels expressed in grams per cubic centimeter. Absolute density (g/cm^3) was estimated by using a grain analyzer (Infratec 1241, FOSS, Laurel, MD).

Compositional Characteristics

Moisture, starch, protein, and oil contents of bulked whole kernels from each line were estimated with near-infrared transmittance (NIT) technology by using the Infratec 1241 grain analyzer. NIT equipment was calibrated and standardized by the Grain Quality Laboratory (GQL) at Iowa State University; the GQL supplies a major portion of the corn and soybean NIR calibration databases of the USDA FGIS.

Wet-Milling Characteristics

Lines were analyzed in the laboratory by using the 100-g modified wet-milling procedure of Singh et al (1997). This procedure yields starch, gluten, fine and coarse fiber, germ, and steepwater fractions. The procedure was slightly modified to improve reproducibility. The 100-g samples were placed in a 500-mL flask and steeped in 300 mL of a solution containing 0.5% lactic acid (lactic acid 85%, Certified A.C.S., Fisher Scientific) and 0.2% sulfur dioxide (sodium bisulfite Certified A.C.S., Fisher Scientific). The corn was steeped in a single batch process in a water bath at 50°C for 40 hr. The starch slurry resulting after the fine grinding and fine fiber separation was placed in a 4-L glass beaker and allowed to settle overnight at 4°C. Starch and gluten was separated the following morning by using the tabling procedure as described by Eckhoff et al (1996). The suspension of starch and gluten flows over an inclined table (2.44 m long and 5.08 cm wide), which allows the starch to settle and the gluten particles, some water-soluble proteins, and water to overflow to the end of the table and be collected in a plastic container. Moisture contents of the recovered fractions were determined in triplicate using Method 14.004 (AOAC 1984). The whole kernel moisture was estimated with three replicates following Approved Method 44-15A (AACC 2000) and used to calculate total solids recovery on a dry basis.

Composition of Recovered Fractions

Protein contents of the starch fractions were determined using the macro-Kjeldahl method, the procedure used by the Corn Refiners Association Method A-18 (CRA 2006). Protein contents in the recovered gluten fractions were determined by using Method 993.13 (AOAC 2003) and a combustion nitrogen analyzer RapidN III from Elementar Americas (Mt. Laurel, NJ) with a protein factor of 6.25. Oil contents in the germ fractions were quantified as crude free fat content according to Methods 14-084 and 14-085 (AOAC 1984) using the Goldfisch procedure.

Statistical Analyses

The procedures Proc GLM and Proc CORR (SAS Institute, Cary, NC) were used to determine statistical differences and correlations among different values, respectively. A linear model was used where lines were considered as a fixed factor. Statistical differences among groups of lines were determined by using contrasts from the GLM procedure. To do statistical comparison of groups of lines, lines were considered as a nested factor within groups. Multiple mean comparisons with least significant differences at $P < 0.05$ ranked groups of lines for compositional and wet-milling characteristics.

RESULTS AND DISCUSSION

Physical Characteristics

Significant differences for test weight, 1000-kernel weight, and absolute density were found (Table I). Test weights of the GEM lines were 73.5–80.4 kg/hL and many were significantly higher than those of B73, Mo17, and the commercial inbred lines used in this study. Our results were in agreement with Singh et al (2001), with test weights of 65.5–85.3 with a mean of 79.3 kg/hL for 51 exotic accessions used in GEM. The TKW weight of the 10 exotic lines was 255.6–341.1 g with a mean value of 297.6 g; these values were similar to those of the adapted lines (mean of 293.4 g). A range of 240–399 g and a mean of 308.5 g was reported by Singh et al (2001). Zehr et al (1995) reported a mean of 268 g when studying the wet-milling properties of 15 inbred lines representatives of the germplasm groups used to produce hybrid seed in the United States. Absolute density had a mean value of 1.301 and

1.272 (g/cm^3) for our exotic and adapted lines, respectively. Zehr et al (1995) and Singh et al (2001) both reported means of 1.32 for adapted inbred lines and exotic accessions, respectively. The relative proportion of vitreous to floury endosperm represents the kernel hardness (Correa et al 2002), which is the main determinant of kernel density. As a consequence, kernel density can be a determining factor of the wet-milling properties of a corn line or hybrid because starch from a softer endosperm is easier to recover during the wet processing of corn due to weaker protein matrices around starch granules (Watson 1987). Because the inbred seed is produced by self-pollination, these differences in physical properties can be attributed not only to genetic differences among lines but also to differences in pollination techniques, especially if several people are doing the pollinations. However, the physical differences among GEM lines, adapted inbred lines, and LAMP accessions in the three studies can also be attributed to differences in growing location because differences in growing environment (variation in soil type, fertility, and climate) can affect the physical properties and the quality of the corn kernels (Watson 1987; Singh et al 2005). This variation in both GEM lines and LAMP accessions shows the great genetic diversity present in exotic corn that can be exploited in advanced breeding programs.

Compositional Characteristics

Starch, protein, and oil contents of the lines (Table I) were statistically different ($P < 0.05$). Starch contents of the GEM lines were slightly higher than for the adapted lines with a mean of 69.7 and 69.0% db for each group, respectively. Some lines with exotic background in the HSEL group had starch contents >70% db (AR285, FS35, and UR11). The HSEL group had a mean starch content of 70.2% db and was statistically superior to the LSEL and adapted groups. These results differ with those reported by Singh et al (2001), where they found that the GEM accessions contained less starch (mean of 67.7% db) than the two Corn Belt inbreds and the two commercial hybrids used as controls. Although comparing results from two different studies has limitations as noted above, it is interesting to compare results of the mean starch contents for B73 and Mo17 for our study (69.5% db) versus Singh et al (2001) (68.5% db), and the means of AR285, FS35, and UR11 (70.7% db) versus the means of the exotic accessions from which the lines were derived (67.5% db) (Singh et al 2001). So, although values for the check lines were higher in our study than those in Singh et al (2001), the mean value of the three HSEL lines was significantly higher than the mean check line value in our study whereas the mean value of the parental accessions was significantly lower than the check value in Singh et al (2001). This indicates that even though Singh et al (2001) concluded that the accessions generally wet-milled poorly, with crossing to adapted germplasm and selection, the resulting progeny lines could be good wet millers.

Protein and oil contents did not vary greatly. The mean protein content was 11.6, 11.9, and 11.5% db for lines with exotic and adapted origins, respectively (Table II). Zehr et al (1995) considered similar values as high and attributed the lower than anticipated starch recovery from wet milling to the negative correlation between protein content and extractable starch (Fox et al 1992; Singh et al 2005). The mean oil contents of 4.2, 4.6, and 4.2% db for HSEL, LSEL, and adapted inbred lines, respectively (Table II), were lower than values reported by Singh et al (2001) who found a mean of 5.2% db for accessions.

TABLE I
Physical and Compositional Characteristics of 10 Corn Lines Introgressed with Exotic Germplasm from the GEM Project and Five Adapted Corn Belt Lines[a]

	Physical Characteristics[b]			Compositional Characteristics		
Line	Test Wt	TKW	Abs Density	Starch	Protein	Oil
AR227	80.4a	282.4f	1.30e	69.8d	11.0g	4.7b
AR285	79.1b	273.9h	1.31cd	70.3c	11.5e	4.4d
CH143	78.3c	269.1i	1.32b	68.3h	12.8a	4.5cd
CH182	80.2a	255.6k	1.33a	69.9d	11.9d	4.0f
CU153	77.7d	267.8i	1.30d	68.9g	12.4b	4.8b
CU562	76.3e	285.7e	1.27fg	69.1g	12.4b	4.6c
FS32	75.6f	331.6b	1.27g	69.4ef	11.5e	5.1a
FS35	79.0b	340.6a	1.32b	70.8b	11.1fg	4.4d
UR11	73.6h	341.1a	1.31c	71.1a	11.4e	3.9g
UR14	74.6g	328.6b	1.29e	69.6e	12.1c	4.2e
Line 1	76.4e	261.2j	1.30e	67.6j	12.8a	4.0f
Line 2	76.3e	291.2d	1.29e	68.0i	11.9cd	4.4d
Line 3	75.3f	295.2c	1.26h	70.4c	10.2h	3.9fg
B73	73.3h	278.5g	1.25i	69.3f	11.2f	4.4d
Mo17	74.4g	341.1a	1.27f	69.8d	11.5e	4.2e
LSD	1.2	3.2	0.01	0.2	0.2	0.2

[a] Values with different letters in the same column are statistically different at $P < 0.05$.
[b] Test weight (kg/hL); TKW, 1000 kernel wt (g); absolute density (g/cm^3).

TABLE II
Compositional Characteristics and Wet-Milling Fraction Yields of Groups of Corn Lines with Exotic and Adapted Origins[a]

	Group of Variables							
	Composition (% db)			Wet-Milling Yields (% db)				
Group of Lines[b]	Starch	Protein	Oil	Starch	Gluten	Fiber	Germ	SR
HSEL	70.2a	11.6b	4.2b	61.4a	17.3a	11.6b	4.4c	87.6a
LSEL	69.2b	11.9a	4.6a	60.8b	17.1a	10.6c	5.8a	87.9a
Adapted	69.0c	11.5c	4.2b	59.6c	16.3b	13.1a	5.2b	86.3b

[a] Values with different letters in the same column are statistically different at $P < 0.05$.
[b] HSEL, high starch exotic lines; LSEL, low starch exotic lines; SR, starch recovery.

Wet-Milling Characteristics

The wet-milling properties of the materials in the present study are shown in Table III. Statistical differences ($P < 0.05$) were found among lines for all variables evaluated. Starch yield is the most important fraction from the wet-milling process (Singh and Eckhoff 1996) and indicates millability, or ease with which kernel components are separated by wet milling. The starch yields of the lines varied significantly with means of 61.4, 60.8, and 59.6% db for the HSEL, LSEL, and adapted groups of lines, respectively (Table II). These values were higher than those for the LAMP accessions used in the GEM project where a mean of 54.3% db was reported (Singh et al 2001). However, the starch yield of the GEM and adapted lines should be compared with caution with those obtained in studies using dent corn hybrids where starch yields are normally higher (Weller et al 1988; Singh and Eckhoff 1996; Singh et al 1997; Dowd 2003, Vignaux et al 2006). The higher starch yields of dent hybrids can be caused by lower protein contents and probably higher proportions of soft to hard endosperm in the corn kernels as indicated by the lower absolute densities reported for these types of hybrids. Hybrids are also much higher yielding than parental inbred lines, thus have a higher proportion of endosperm to embryo, endosperm being primarily starch. The mean starch yield for the adapted inbreds was 59.6% db; this value is higher than the mean value of 56.2% db reported by Zehr et al (1995) for a group of adapted inbred lines.

GEM lines AR227 and CU562 had starch yields statistically similar to the best adapted inbred line B73 (Table III), indicating not only that exotic germplasm can be introgressed into adapted lines without detrimental effect on wet milling, but that exotic germplasm may even have potential to improve wet-milling characteristics of hybrids. Additionally, accessions from Argentina have been among the highest in grain yield in LAMP, and even though they lacked flowering synchrony and had poor stalk strength, they showed excellent grain yield potential (Salhuana et al 1998). Lines introgressed with the accession CUBA117 have good yield potential when test-crossed to an elite adapted inbred line and then evaluated for agronomic performance in yield trials (Pollak 2003). Both of the above lines had starch recovery values ≈11 percentage points higher than their parental exotic accessions (Singh et al 2001). It is interesting to note that AR227 was classified in the LSEL group based on Cerestar data.

Gluten yields were 15.0–19.5 with a mean of 17.3 and 17.1% db for the HSEL and LSEL groups of lines, respectively, which were not statistically different; the yield of the group of adapted inbreds was 13.6–18.9 with a mean of 16.3% db, which was statistically different from both GEM line groups (Table II). The values are higher than those reported for LAMP accessions (Singh et al 2001), adapted lines (Zehr 1995), or commercial dent hybrids (Fox et al 1992; Singh et al 1997; Dowd 2003; Vignaux et al 2006). This poor starch-gluten separation can be attributed to high protein content of these lines and to the presence of a protein matrix surrounding the starch granules, which makes the release of starch granules more difficult, although LAMP accessions would also have these characteristics (Watson 1984).

Fiber yield was lower than values reported by Singh et al (2001) and Zehr et al (1995) but germ and steepwater yields were similar in these two studies (Table III). There were significant differences for fiber yield among groups of lines (Table II).

Starch recovery (SR) is calculated by dividing starch yield by starch content and provides an excellent indicator of the millability of any corn material as the extractable starch obtained from wet milling. In our study, SR was 83.0–92.1% with a mean of 87.7% for both groups of exotic inbred lines (Tables II and III). These values were higher and had less variation than those re-

TABLE IV
Composition of Recovered Fractions from Wet Milling of 10 Corn Lines Introgressed with Exotic Germplasm from the GEM Project and Five Adapted Corn Belt Lines[a]

	Recovered Fractions (% db)[b]		
Line	PStarch	PGluten	Oil
AR227	0.31a	44.5bc	60.2b
AR285	0.26bc	40.7ef	58.8bc
CH143	0.28ab	38.7fg	59.0bc
CH182	0.27a–c	38.3g	51.4gh
CU153	0.28ab	41.2de	56.4de
CU562	0.30ab	43.3b–d	58.8bc
FS32	0.28ab	40.5ef	49.5h
FS35	0.30ab	39.1e–g	54.4ef
UR11	0.29ab	40.2e–g	57.7cd
UR14	0.30ab	42.9cd	53.4fg
Line 1	0.28ab	40.6ef	63.8a
Line 2	0.28ab	39.9e–g	63.4a
Line 3	0.23c	45.2b	63.8a
B73	0.29ab	48.0a	50.2h
Mo17	0.29ab	43.5bc	47.2i
LSD	0.04	2.2	2.2

[a] Values with different letters in the same column are statistically different at $P < 0.05$.
[b] Protein content in starch and gluten samples, respectively; oil content in germ fraction.

TABLE III
Wet-Milling Fraction Yields of 10 Corn Lines Introgressed with Exotic Germplasm from the GEM Project and Five Adapted Corn Belt Lines[a]

	Wet-Milling Characteristics (% db)[b]						
Line	Starch	Gluten	Fiber	Germ	Steepwater	SR	TSR
AR227	64.3a	15.0e	10.1k	5.2de	5.2de	92.1a	99.7a–d
AR285	61.6ef	17.9b	11.0gh	4.0g–i	5.3d	87.7c	99.8a–c
CH143	56.4i	19.5a	10.7hi	7.5a	5.5c	82.6ef	99.6b–d
CH182	62.5cd	17.4bc	10.1k	4.5e–h	5.1e–g	89.5b	99.5cd
CU153	61.0fg	17.2b–d	10.9hi	5.0d–f	5.3d	88.6bc	99.4de
CU562	63.1bc	16.9b–d	10.5ij	4.2f–i	5.1fg	91.4a	99.8a–c
FS32	60.7g	16.7cd	10.2jk	6.5bc	5. 8b	87.5c	99.9ab
FS35	59.1h	17.5bc	12.6e	5.7cd	5.0g	83.4e	99.8a–c
UR11	60.9fg	16.8cd	13.6c	3.6i	5.1e–g	85.7d	99.9ab
UR14	61.9de	16.8cd	11.4fg	4.7e–g	5.1fg	89.0b	99.9ab
Line 1	55.1j	18.9a	15.7a	3.9g–i	5.9b	81.5f	99.4d
Line 2	56.5i	17.7bc	15.2b	3. 7hi	6.1a	83.1e	99.1e
Line 3	62.7c	13.6f	13.0d	5.2de	5.0fg	89.1b	99.5cd
B73	63.9ab	15.0e	9.6l	6.5bc	5.1e–g	92.2a	100.0a
Mo17	59.8h	16.2d	11.7f	6.8ab	5.1ef	85.7d	99.6b–d
LSD	0.8	1.0	0.4	0.9	0.2	1.2	0.3

[a] Values with different letters in the same column are statistically different at $P < 0.05$.
[b] Steepwater; SR, starch recovery; TSR, total solids recovery.

TABLE V
Correlation Coefficients Between Physical, Compositional, and Wet-Milling Characteristics of 10 Corn Lines Introgressed with Exotic Germplasm from the GEM Project and Five Adapted Corn Belt Lines[a]

	Physical Characteristics[b]			Compositional Characteristics		
Fraction Yields[c]	Test Wt	TKW	Abs Density	Starch	Protein	Oil
Starch	–0.01	0.03	–0.34	0.58*	–0.55*	0.14
Gluten	0.31	–0.22	0.65*	–0.49	0.83**	0.05
Fiber	–0.23	0.12	0.11	–0.24	0.09	–0.53*
Germ	–0.06	0.16	–0.22	–0.03	–0.09	0.38
Steepwater	0.03	–0.24	0.01	–0.75*	0.45	0.29
SR	–0.01	–0.15	–0.44	0.32	–0.38	0.26
TSR	–0.24	0.41	–0.18	0.55*	–0.23	0.13

[a] * and ** indicate statistical significance at 0.05 and 0.01 probability levels, respectively.
[b] Test Wt, test weight; TKW, thousand kernel weight; absolute density (g/cm^3).
[c] Steepwater yield; SR, starch recovery; TSR, total solids recovery.

ported by Singh et al (2001), which indicates that the procedure had a good reproducibility but also represents the positive effect on millability of exotic germplasm by crossing to adapted germplasm. SR for the adapted inbred lines was 81.5% for Line 1 and 92.2% for B73 with an overall mean of 86.3%, similar to the mean value reported by Zehr et al (1995) of 84.8% for a set of adapted inbred lines. Total solids recovery (TSR) was 99.1–99.9% and is similar to the values reported for the industry of 99.6–100% (Singh and Eckhoff 1996).

Composition of Recovered Fractions

Composition of some recovered fractions are shown in Table IV. The protein contents of the starch fractions were 0.26–0.31%. According to Vignaux et al (2006), the typical level of residual protein in commercial starch is 0.3% but has a range of 0.27–0.32% (Watson 1984). Singh et al (2001) reported an average of 1.05% of protein content in starch from GEM accessions and attributed this to poor starch-gluten separation that can be a characteristic of lines, either adapted or exotic origin, that have a high level of protein content in the corn kernels.

Protein contents of gluten samples were 38.3–44.5% for the exotic lines. These values were lower than typical industry samples of ≈66% (Dowd 2003) but were similar to values of 42.4% reported by Singh et al (2001). This low protein content has been attributed to the difficulty to separate starch from the gluten fractions, which results in higher gluten yields with a high concentration of starch and, as a consequence, lower protein contents in the gluten samples. Gluten obtained when using the tabling method to make the starch-gluten separation rarely contains >50% protein content (Watson 1984).

The oil content in the germ fraction averaged 56.0% with a range of 49.5–60.2% for the 10 GEM lines. The commercial lines had a mean of 63.7%. These values were high compared with those reported for high-oil corn hybrids of 52.5–57.1% (Raush et al 1999). However, we assume they are correct because random samples were rerun, including samples from the commercial lines, and the results were the same. Vignaux et al (2006) reported values of 47.9–54.7% for several commercial corn dent hybrids.

Single Factor Correlations

Correlation coefficients of the physical and compositional characteristics with the wet-milling properties of the materials under study (Table V) varied but they followed the same pattern reported in previous studies (Fox et al 1992; Zehr et al 1995; Singh et al 2001). As expected, the starch yield was positively correlated with starch content and negatively correlated with protein content in the corn kernels. This is important because now it is possible to easily screen new inbred lines and hybrids for compositional characteristics during early stages of breeding programs using NIT technology and then make initial selection decisions based on this information if materials with high-extractable starch are desired. Gluten yield had a significant negative correlation with starch yield (data not shown) and this variable was also highly correlated with absolute density and compositional protein of the corn kernels. The first correlation indicates that corn cultivars with lower absolute densities and lower protein content would be preferred if high starch yield is the primary consideration in selection.

CONCLUSIONS

Groups of lines were statistically different and the HSEL group showed higher starch content, starch yield, and starch recovery than the LSEL group, which means that they had better millability and more appropriate wet-milling characteristics for the corn processing industry. AR16035:S19-227-1-B and CUBA117:S1520-562-1-B had similar wet-milling characteristics, related to starch yield, as the Corn Belt inbred line B73 which is considered to have good millability. These exotic lines were developed and selected for high grain yield as test-crosses in yield trials, which is evidence that there is potential in exotic germplasm to improve the agronomic performance and maintain and even improve wet-milling characteristics of hybrids grown in the United States.

GEM lines in this study had higher starch yields and starch recoveries than the group of LAMP accessions used in GEM that were evaluated by Singh et al (2001). This improvement of the millability of GEM lines may be an effect of the adapted germplasm to increase the starch and reduce the protein contents in relation to the values of the accessions, through breeding by pedigree selection.

There was a positive correlation between starch content and starch yield and a negative correlation between protein content and starch yield. This indicated that genotypes with high starch and low protein contents will produce higher and purer starch yields. NIT technology may be used as a predictive tool to screen early progeny for high starch yield and save time and costs in a corn breeding program directed at improving wet-milling efficiency in corn given by the extractable starch available in the corn kernels.

LITERATURE CITED

AACC International. 2000. Approved Methods of the American Association of Cereal Chemists, 10th Ed. Method 44-15A. The Association: St. Paul, MN.
AOAC. 1984. Official Methods of Analysis of the Association of Official Analytical Chemists. 14th Ed. Method 14.004. The Association: Washington, DC.
AOAC. 2003. Official Methods of Analysis of AOAC International. Method 993.13. AOAC International: Gaithersburg, MA.
Butzen, S., and Hobbs, T. 2002. Corn processing. Crop Insights 12:1-6.
Correa, C. E. S., Shaver, R. D., Pereira, M. N., Lauer, J. G., and Kohn, K. 2002. Relationship between corn vitreousness and ruminal in situ starch degradability. J. Dairy Sci. 85:3008-3012.

CRA. 2006. Analytical Methods of the Member Companies of the Corn Refiners Association. Method A-18 (online). CRA: Washington, DC.

Dijkhuizen, A., Dudley, J. W., Rochford, T. R., Haken, A. E., and Eckoff, S. R. 1998. Near-infrared reflectance correlated to 100-g wet-milling analysis in maize. Cereal Chem. 75:266-270.

Dowd, M. K. 2003. Improvements to laboratory-scale maize wet-milling procedures. Indus. Crops Prod. 18:67-76.

Eckoff, S. R., Singh, S. K., Zehr, B. E., Raush, K. D., Fox, E. J., Mistry, A. K., Haken, A. E., Niu, Y. X., Zou, S. H., Buriak, P., Tumbelson, M. E., and Keeling, P. L. 1996. A 100-g laboratory corn wet milling procedure. Cereal Chem. 73:54-57.

FGIS. 1988. Test weight per bushel apparatus. In: Grain Inspection Handbook. II. USDA. FGIS:Washington, DC.

Fox, S. R., Johnson, L. A., Hurburgh, Jr., C. R., Dorsey-Redding, C., and Bailey, T. B. 1992. Relations of grain proximate composition and physical properties to wet-milling characteristics of maize. Cereal Chem. 69:191-197.

Goodman, M. M. 1985. Exotic maize germplasm: Status, prospects, and remedies. Iowa State J. Res. 59:497-527.

Goodman, M. M. 1999. Broadening the genetic diversity in maize breeding by use of exotic germplasm. In: The Genetics and Exploitation of Heterosis in Crops. J. G. Coors and S. Pandey, eds. ASA-CSSA-SSSA: Madison, WI.

Pollak, L. M. 2003. The history and success of the public-private project on Germplasm Enhancement of Maize (GEM). Adv. Agron. 78:45-87.

Raush, K. D., Fox, E. J., and Eckhoff, S. R. 1999. Wet milling characteristics of high oil corn hybrids. Starch 51:411-415.

Salhuana, W., and Smith, S. 1998. Maize breeding and genetic resources. In: Agricultural Values of Plant Genetic Resources. R. E. Evenson, D. Gollin, and V. Santaniello, eds. CABI: New York.

Salhuana, W., Jones, Q., and Sevilla, R. 1991. The Latin American Maize Project: Model for rescue and use of irreplaceable germplasm. Diversity 7:40-42.

Salhuana, W., Pollak, L. M., Ferrer, M., Paratori, O., and Vivo, G. 1998. Breeding potential of maize accessions from Argentina, Chile, USA, and Uruguay. Crop. Sci. 38:866-872.

Singh, M., Paulsen, M. R., Tian, L., and Yao, H. 2005. Site-specific study of corn protein, oil, and extractable starch variability using NIT spectroscopy. Appl. Eng. Agric. 21:239-251.

Singh, N., and Eckhoff, S. R. 1996. Wet milling of corn–A review of laboratory-scale and pilot plant-scale procedures. Cereal Chem. 73:659-667.

Singh, S. K., Johnson, L. A., Pollak, L. M., Fox, S. R., and Bailey, T. B. 1997. Comparison of laboratory and pilot-plant corn wet-milling procedures. Cereal Chem. 74:40-48.

Singh, S. K., Johnson, L. A., Pollak, L. M., and Hurburgh, C. R. 2001. Compositional, physical, and wet milling properties of accessions used in Germplasm Enhancement of Maize Project. Cereal Chem. 78:330-335.

USDA. 2007. Feed grains database: Yearbook tables. Economic Research Service. USDA: Washington, DC.

Vignaux, N., Fox, S. R., and Johnson, L. A. 2006. A 10-g laboratory wet-milling procedure for maize and comparison with larger scale laboratory procedures. Cereal Chem. 83:482-490.

Watson, S. A. 1984. Corn and sorghum starches: Production. Pages 417-468 In: Starch: Chemistry and Technology. R. L. Whistler, J. N. BeMiller, and E. F. Paschall, eds. Academic Press: San Diego, CA.

Watson, S. A. 1987. Corn structure and composition. Pages 53-82 in: Corn: Chemistry and Technology. S. A. Watson and P. E. Ramstad, eds. AACC Interational: St. Paul, MN.

Weller, C. L., Paulsen, M. R., and Steinberg, M. P. 1988. Correlation of starch recovery with assorted quality factors of four corn hybrids. Cereal Chem. 65:392-397.

Zehr, B. E., Eckhoff, S. R., Singh, S. K., and Keeling, P. L. 1995. Comparison of wet-milling properties among maize inbred lines and their hybrids. Cereal Chem. 72:491-497.

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